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TEAL WING OWR PROGRAM, SEMI-ANNUAL
TECHNICAL REPORT FOR PERIOD ENDING
30 SEPTEMBER 1973

Robert B. Wagner

ITT Electro-Physics Laboratories, Incorporated

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13 ABSTRACT

Progress to date of report consists of:

- (a) Two of the three seasonal measurements of at-sea natural noise have been made and partially analyzed. Preliminary results were published in Project Report No. 233.
- (b) The suitability of existing, fleet-deployed antennas for the intended class of service was investigated and reported in the same Project Report No. 233.
- (c) The channel characterization experiments, performed during August 1973 between Cape Cod and two points on the coast of Maine (100 and 220 nm) are described under the following categories: equipment, physical set-up, and some preliminary data results which indicate that dispersion is insignificant on the surface-wave mode for the environmental conditions prevailing during the test period.

Analysis of data is continuing and will be reported with the winter solstice noise measurement data, approximately February 1974.

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**TEAL WING OWR PROGRAM
SEMI-ANNUAL TECHNICAL REPORT
FOR PERIOD ENDING
30 SEPTEMBER 1973**

October 1973

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FOR PERIOD ENDING
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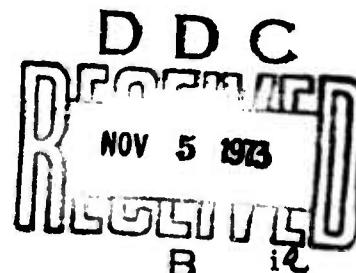
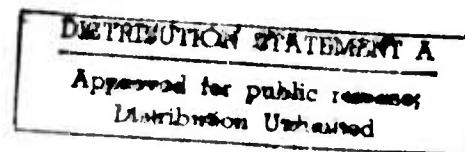


TABLE OF CONTENTS

Section	Page
1. INTRODUCTION	1-1
2. PROGRESS THROUGH SEPTEMBER 1973	2-1
2.1 Summary of Progress	2-1
2.2 The Channel Measurements	2-2
3. TECHNICAL DESCRIPTION OF CHANNEL MEASUREMENT EXPERIMENT	3-1
3-1 Transmitting Terminal Equipment	3-1
3-2 Receiving Terminal Equipment	3-1
3-3 The Swept-Format Generation	3-1
3-4 Modes of Operation	3-9
4. PRELIMINARY CHANNEL MEASUREMENT RESULTS	4-1
4-1 Spectral Analysis	4-4
4-2 Comparison with Skywave Dispersion	4-4
4-3 Characterization of Dispersion	4-7

LIST OF TABLES

4-1 Sea State Hindcasts for the Data Presented in Figure 4-6	4-12
4-2 Algorithm Used to Derive the Distortion Loss Values of Figure 4-7	4-15

LIST OF FIGURES

Figure		Page
2-1	Channel Measurement Paths	2-3
2-2	12-Wire Folded Monopole, 1.5-6 MHz Configuration	2-5
2-3	90' Antenna Model (Impedance Chart)	2-6
2-4	Antenna Losses	2-7
2-5	Cape Cod Installation	2-9
2-6	Cape Elizabeth Installation	2-10
2-7	West Quoddy Head Installation	2-11
3-1	Transmitting Equipment	3-2
3-2	Receiving Equipment	3-3
3-3	Transmitter Control	3-4
3-4	Transmit Control Chassis	3-6
3-5	Receiver Control	3-8
3-6	Receive Control Chassis	3-10
4-1	Spectrogram of Received Signal with Receiver Directly Coupled to Transmitter	4-3
4-2	Representative Spectrogram of Surface-Wave-Propagated Signals	4-5
4-3	Spectrogram of Signals Propagated via the F-Region of the Ionosphere	4-6
4-4	Phase Angle vs. Frequency Plot of the F-Mode Data of Figure 4-3	4-8
4-5	Phase Angle vs. Frequency Plot for the Surface Wave Data of Figure 4-2	4-9
4-6	Surface Wave Distortion Factors as a Function of Frequency Band	4-10
4-7	Derived Relationship between Distortion Factor, Distortion Loss and Signal Bandwidth	4-14

1. INTRODUCTION

The ITT Electro-Physics Laboratories, Inc. (ITT-EPL) has been under ARPA funding since late January 1973 to provide studies and measurements applicable to the TEAL WING Over Water Research Program. For further background, reference is made to ITT-EPL Project Report No. 229, "TEAL WING OWR PROGRAM SEMI-ANNUAL TECHNICAL REPORT FOR PERIOD ENDING 30 MARCH 1973." Work has proceeded in accordance with the original schedule as modified by ITT-EPL letters of 2 January 1973 and 24 April 1973, of which the latter indicates our intention to accelerate some of the reporting, as evidenced by information contained in the second quarterly report, "ITT-EPL Project Report No. 233, "TEAL WING OWR PROGRAM, SUPPLEMENTARY TECHNICAL REPORT FOR PERIOD ENDING 30 JUNE 1973."

This is the third quarterly report on the program and addresses work performed subsequent to 1 July 1973.

2. PROGRESS THROUGH SEPTEMBER 1973

2.1 SUMMARY OF PROGRESS

The three primary objectives of the OWR program for the present contract period are restated here:

- (1) Design and perform experiment to record instantaneous wide-bandwidth noise levels in the 1.5 to 6 MHz regime at sea, during equinoctial, summer solstice and winter solstice periods. Process data to establish merits of various noise abatement and/or excision techniques.
- (2) Investigate existing and planned shipboard antennas for wide-band operation at 1.5 - 6 MHz. Study theoretical parameters of such installations to maximize surface-wave response.
- (3) Design and perform channel characterization experiment with primary focus on dispersion, if any, as a function of sea state and atmospheric conditions over a sea surface path of approximately 150 and 300 miles in the same frequency regime. Verification of prior path loss measurements is a secondary objective.

And, of course, the findings of the above are to be presented in a manner useful to designers of systems for surface-wave applications.

As to the first task -- two of the three at-sea measurements have been made, in the equinoctial and summer solstice periods, and preliminary data displayed at a meeting of the TEAL WING community, July 25-26 at SRI, as well as in ITT-EPL Project Report No. 233, "TEAL WING OWR Program Supplementary Technical Report for Period Ending 30 June 1973." (This report was limited in distribution due to its classification, resulting from discussion of certain factors of the second task above.) A final data report on the noise measurements will be proffered after the winter solstice data has been analyzed. This data-taking voyage will be made on the first available trip of the GTS Wm. M. Callaghan after 21 December 1973.

The second task was reported in the Project Report No. 233 and will not be treated here.

The remainder of this report will address the third task, for which the field measurements were completed 31 August 1973 and for which preliminary data is included herein.

2.2 THE CHANNEL MEASUREMENTS

Arrangements were made with the First District Headquarters of the U.S. Coast Guard, with assistance from ONR, to use appropriate siting at land-sea interfaces across the Gulf of Maine. Additionally, permission for transmission of a swept-frequency format was requested of and approved by the FCC, under the call sign KB2XFZ, for experimental use through August 1973.

The channel measurement paths were from Cape Cod to two places on the coast of Maine. As shown in Figure 2-1, the lengths of these paths are approximately 100 and 220 nm. The transmitter was located at the Race Point Coast Guard Station, and employed a swept-sounder format. A synchronized swept-frequency receiver was first located at the Cape Elizabeth Coast Guard Station and subsequently relocated to a site near the West Quoddy Head Coast Guard Station. Antennas at both locations were broadband, vertically polarized, folded monopoles, 90 feet in height; details of the installation are given later.

A large amount of data was not required to be taken, but it was intended that the data be taken over as wide a variety of sea states and atmospheric conditions as possible. Sea state information was obtained from both the U.S.N Oceanographic Office and the Master's Log of the M/S BOLERO, a luxury ferry which crosses the mouth of the Bay of Fundy, from Portland, Me. to Yarmouth, Nova Scotia, one round trip each day. Atmospheric ducting was intended to be sampled for existence by a corroborative sampling near 100 MHz by each terminal attempting to receive broadcast FM stations at the other end of the path; this effort turned out to be futile for the period of the experiment. Dispersion, if any, was and is of primary concern, with verification of path loss measurements made by other investigators as a secondary objective. Preliminary data analysis is given in Section 4.

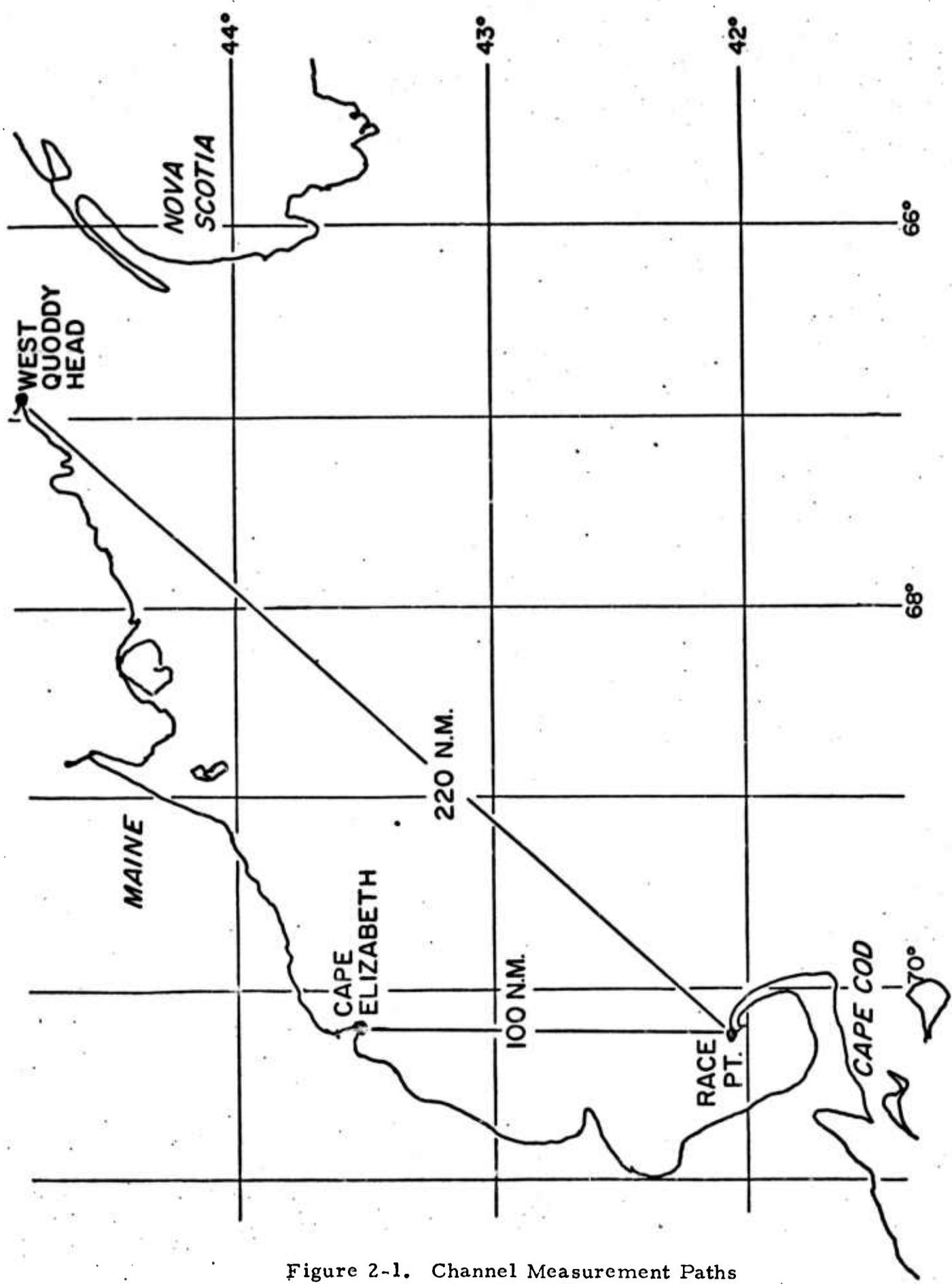


Figure 2-1. Channel Measurement Paths

2.2.1 The Antenna

The problem of coupling vertically polarized energy at low vertical angles, in the frequency range of 1.5 to 6 MHz, was of some concern in the choice of antenna configuration in the matter of required ease of installation. Various configurations of elements, using 90-foot crank-up towers (the largest deemed practical) were assessed and some configurations measured on the EPL model range. The chosen configuration and the Model impedance characteristic are shown in Figures 2-2 and 2-3 respectively.

Impedance measurements of full-scale erected antennas were made at the first two sites and are shown in Figure 2-4 in the form used in the data analysis described later.

2.2.2 Physical Arrangements

Two leased van trucks were used for housing the equipments for the experiment. The receiving equipment truck was larger than the transmitting equipment truck, in order to transport the 90-foot antenna towers on its roof. Additional bracing was provided on the receiving equipment truck to support the weight of the towers. The vertical clearance of that truck and towers just met ICC requirements and so great care in routing and driving was required, especially on secondary roads where telephone lines cross in abundance.

One rack of electronic equipment was located in the transmitter (smaller) van. The equipment configuration in the receiver van was a full rack, plus the incremental digital tape recorder, calibration and monitoring equipment on a table for ease of operating and logging of data.

Both terminals had Collins SSB HF transceivers, using whip antennas, and FM receivers using folded dipole antennas. These smaller antennas were later erected on the roofs of the trucks on site.

One full-scale, 90-foot antenna was test-erected on the EPL grounds to check procedures and to train the personnel. The electronic equipments were exercised in the vans to verify synchronizing procedures and to make a final test tape (without antenna characteristics) at EPL.

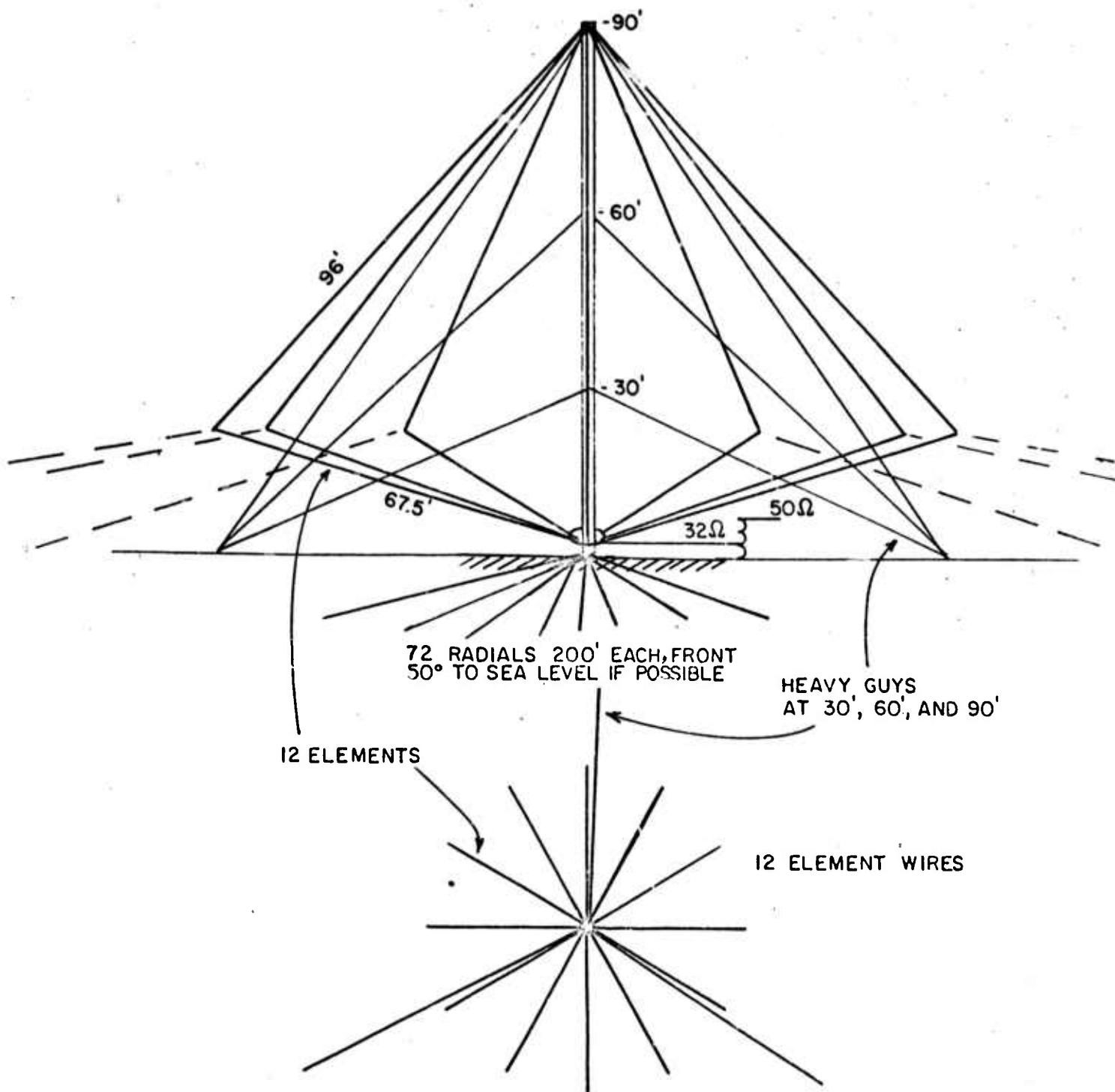
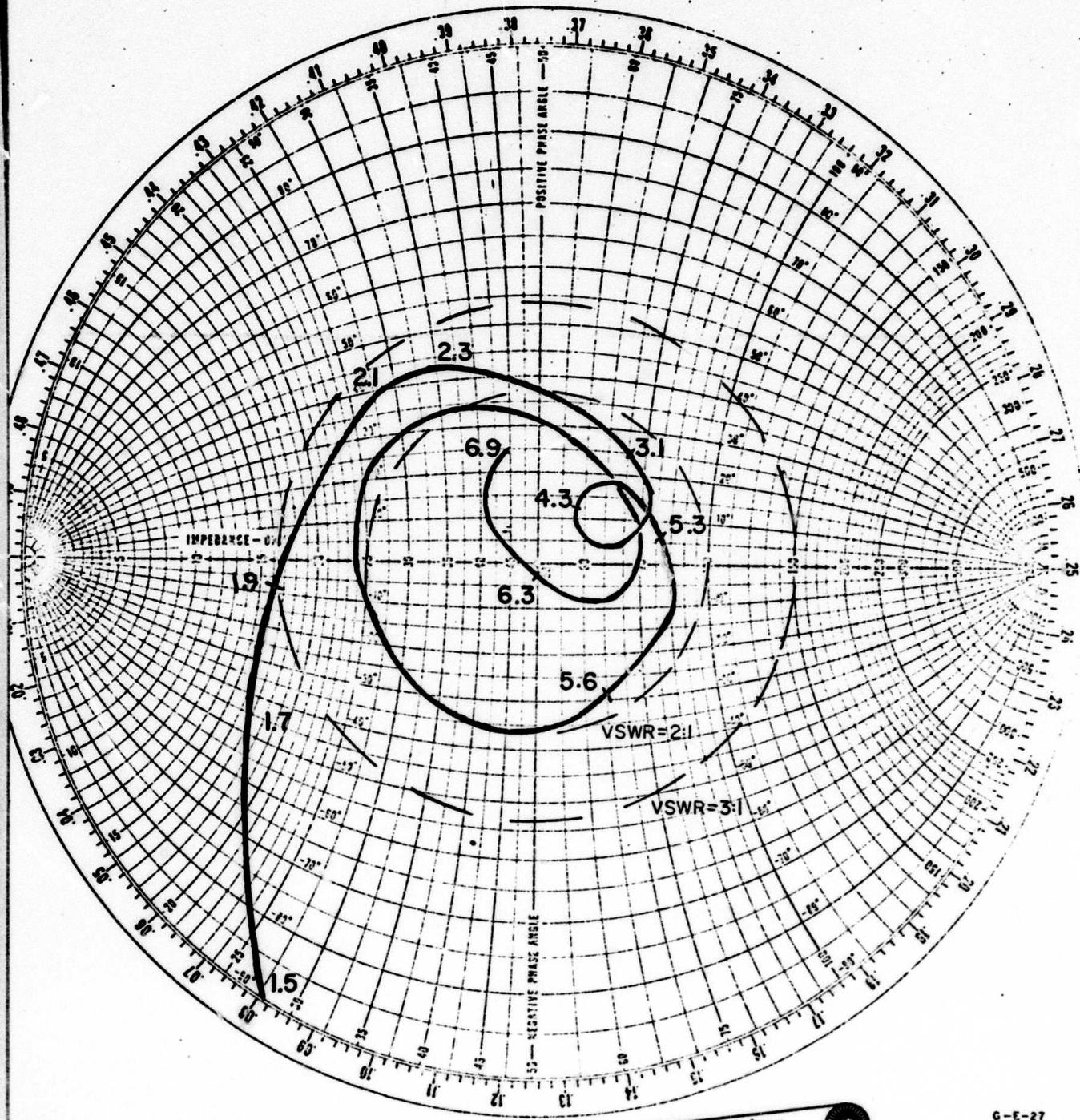


Figure 2-2. 12-Wire Folded Monopole, 1.5-6 MHz Configuration



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Figure 2-3, 90' Antenna Model, $Z_0 = 50 \Omega$

Z- θ CHART
MODEL 803A VHF BRIDGES
 HEWLETT-PACKARD COMPANY
 PALO ALTO, CALIFORNIA

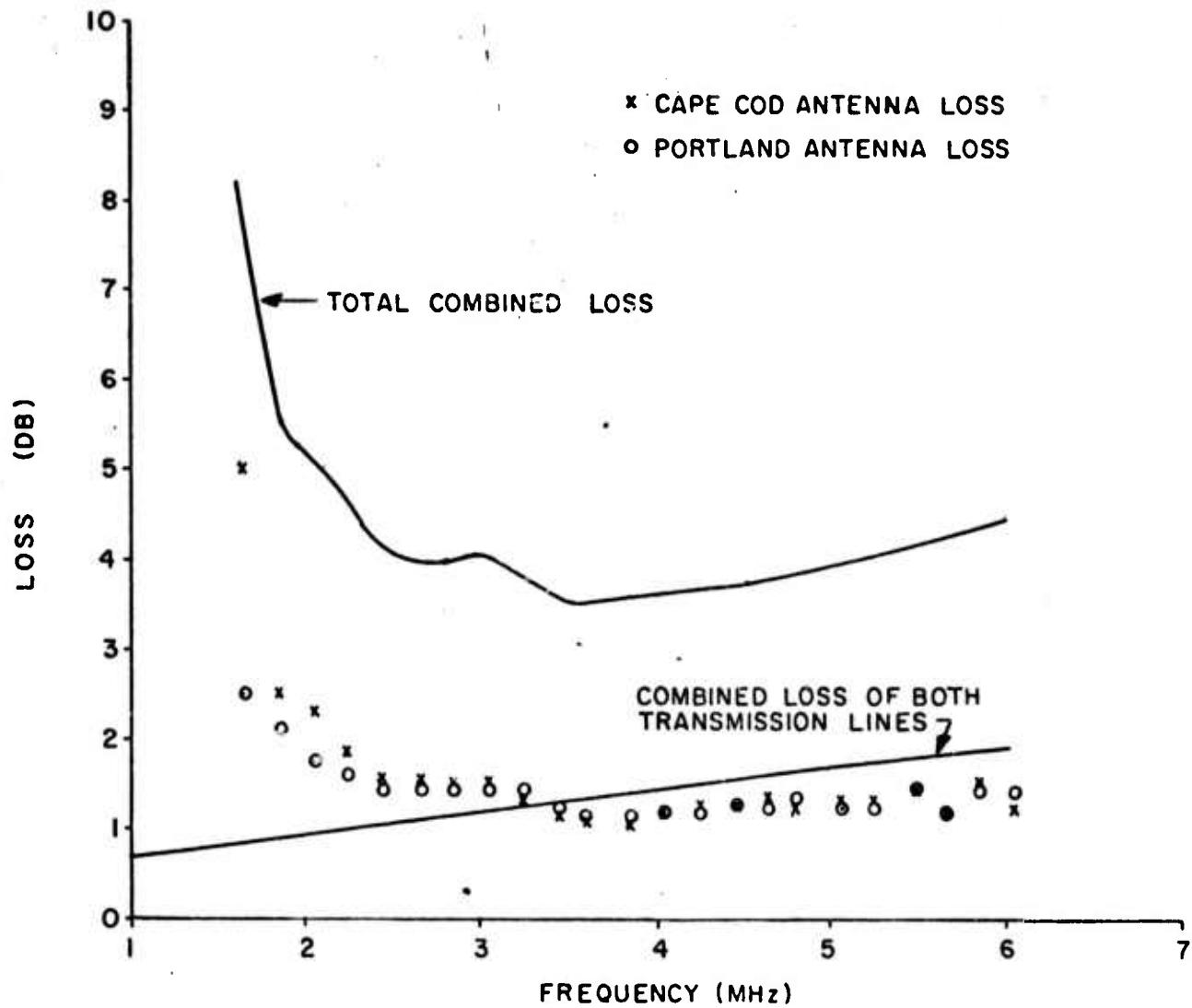


Figure 2-4. Antenna Losses

2.2.3 Cape Cod Site Installation

Both trucks and four men arrived at the Race Pt. Coast Guard Station, Cape Cod, Mass., on 1 August 1973. The antenna installation was made under considerable difficulty due to the fineness of the sand. Figure 2-5 shows the Race Point antenna installation, looking in the direction of propagation interest. The truck was backed to the top of the slope, on landing mats, to within 250 feet of cable to the antenna. The antenna impedance was measured after the installation was completed; data mentioned previously.

The receiving equipment was set up inside its van, and operated with a foreshortened stub antenna at approximately 700 ft. distance from the transmitting antenna. A test tape was made under this setup to calibrate the installed characteristics of the one (transmitting) full-scale antenna.

2.2.4 Cape Elizabeth Site Installation

The receiving equipment van then departed for Cape Elizabeth early on 6 August and commenced installation on 7 August, somewhat farther from the shoreline (approximately 700 feet) than originally planned due to commercial build-up (restaurant, picnic area, etc.). This site was ready to operate on 9 August. The land-line telephone being some distance away, SSB transceivers were shipped to both sites and used for experiment control. ONR allocations and call sign (NER-2/3) were used. Again, antenna impedance was measured. Data taking started on 10 August and continued through 20 August. Figure 2-6 shows the Cape Elizabeth installation.

2.2.5 West Quoddy Hd. Site Installation

The equipment was dismantled at the first receiving site (100 nm path) on the 21st and transported on the 22nd. Upon arrival at the West Quoddy Head C.G. Station, that site was deemed unusable for several reasons -- waist-high underbrush over the entire array on terrain too wet to allow a tractor to enter, masking to the SSE by other structures, and a navigation beacon at 40 W PEP which turned out to transmit in a steady-state mode under fog conditions. Fortunately, an ideal siting was arranged on private property about three miles south of the CG Station. That installation was completed and operations commenced by noon on the 24th of August. Figure 2-7 shows the installation.

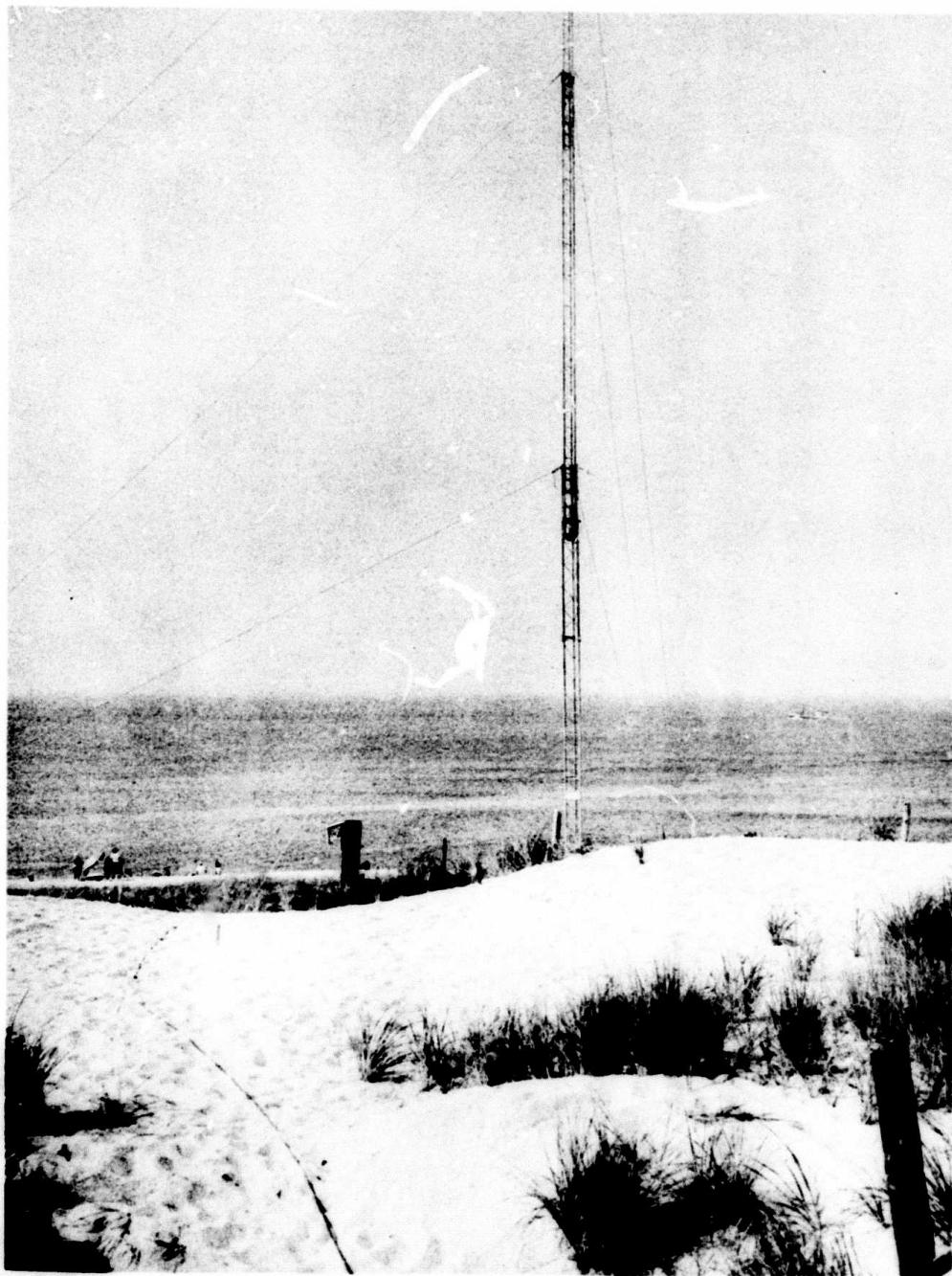


Figure 2-5. Cape Cod Antenna Installation



Figure 2-6. Cape Elizabeth Installation

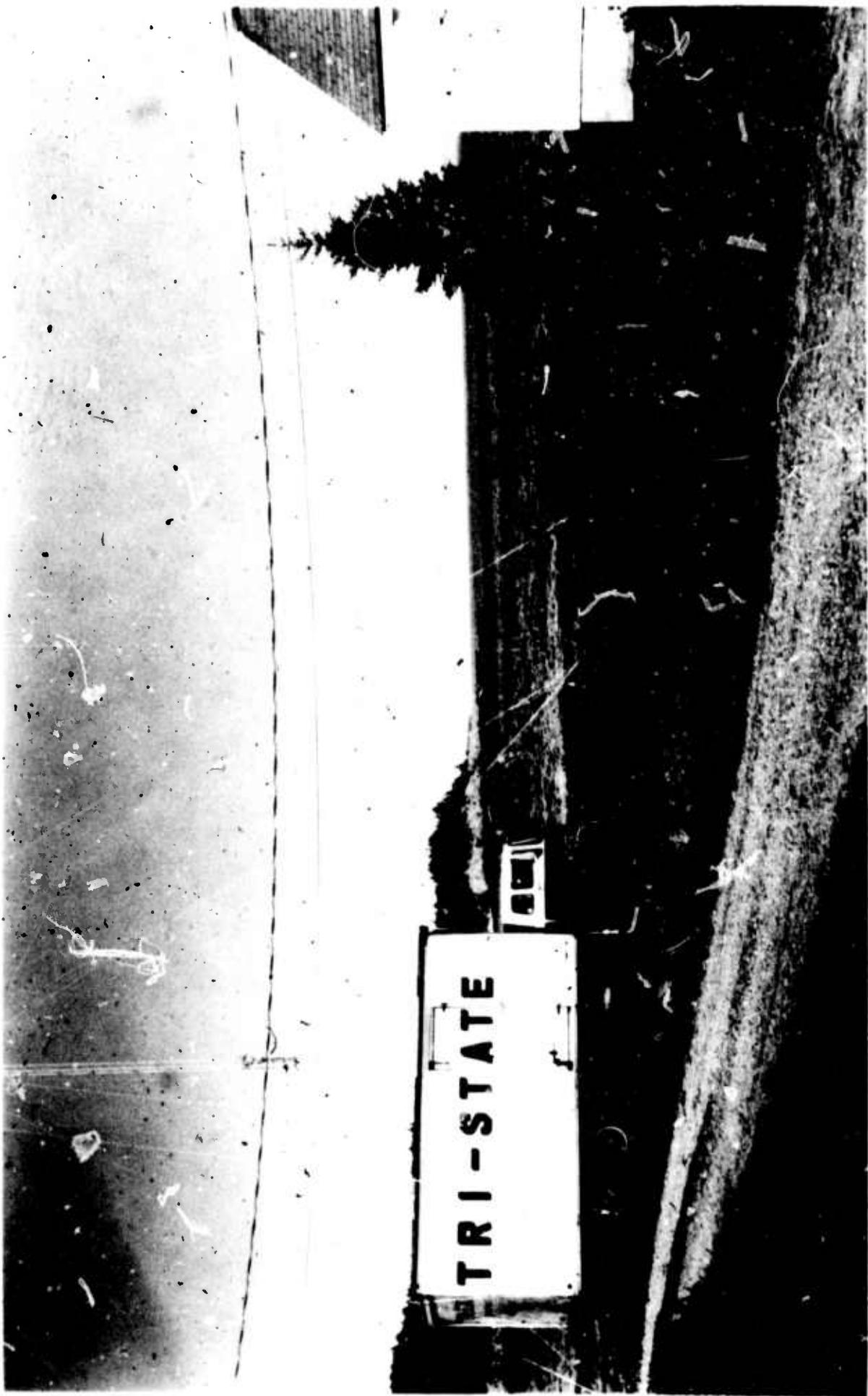


Figure 2-7. West Quoddy Head Installation

2.2.6 Experiment Wrap-up

The operations were terminated in late evening on August 31 and the stations dismantled over the next several days -- so scheduled to avoid truck travel on the Labor Day weekend.

Upon arrival at EPL, the equipments were again checked back-to-back with suitable attenuation, and another calibration tape made.

3. EQUIPMENT DESCRIPTION FOR THE CHANNEL MEASUREMENT

The TEAL WING OWR channel measurement system comprised transmitting and receiving equipment located separately at each end of the path. Both units were operated over a range of frequencies, in synchronism, controlled by hardware programmers at each location. Initial synchronization was accomplished by operators at each end of the path monitoring transmissions of time standards (WWV or CHU).

3.1 TRANSMITTING TERMINAL EQUIPMENT

The swept-frequency excitation equipment (described in 3.3), the transmitter and controls, along with a commercial receiver (Racal) for gross synchronizing, were mounted in one rack as shown in Figure 3-1. The transmitter, an ENI-350L, was driven by the stepped excitation with amplitude control provided by an attenuator mounted with test points on the connector interface panel at the top of the rack.

3.2 RECEIVING TERMINAL EQUIPMENT

Similar frequency-stepping receiver injections into the TEAL WING receiver, and interface logic to the incremental tape recorder (as used in the noise measurement experiments) are mounted in one rack along with the necessary synthesizers and power supplies as shown in Figure 3.2.

3.3 THE SWEPT-FORMAT GENERATION

There are four operating bands, each 896 kHz wide, which contain 4,480 discrete frequency steps. The frequency is swept linearly at a rate of 10 MHz per second in 200 Hz increments (stepped every 20 microseconds). This sweep action is provided by programmed Rockland frequency synthesizers operated between 1.000 and 1.896 MHz.

The Transmit Control block diagram, Figure 3-3, shows the technique utilized to generate the 200 Hz increments. A constant of 200 is added to the instant count and is clocked into a register every 20 microseconds.

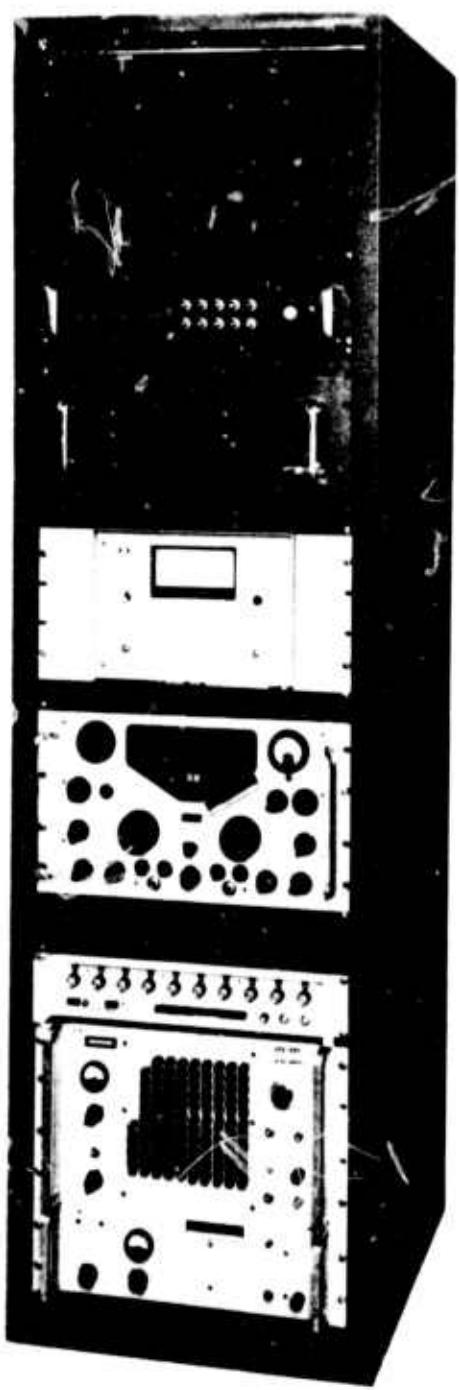


Figure 3-1. Transmitting Equipment

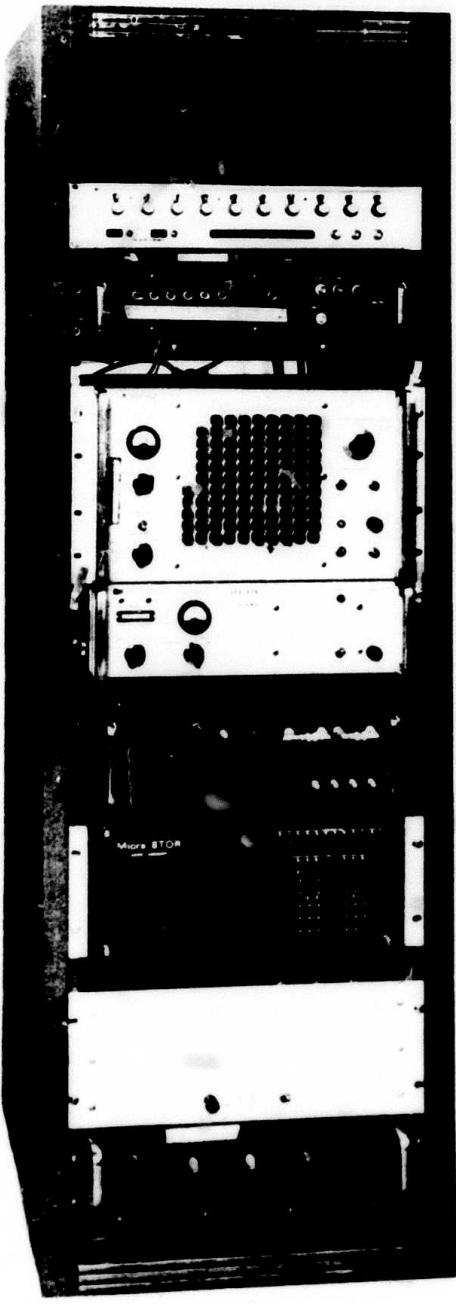


Figure 3-2. Receiving Equipment

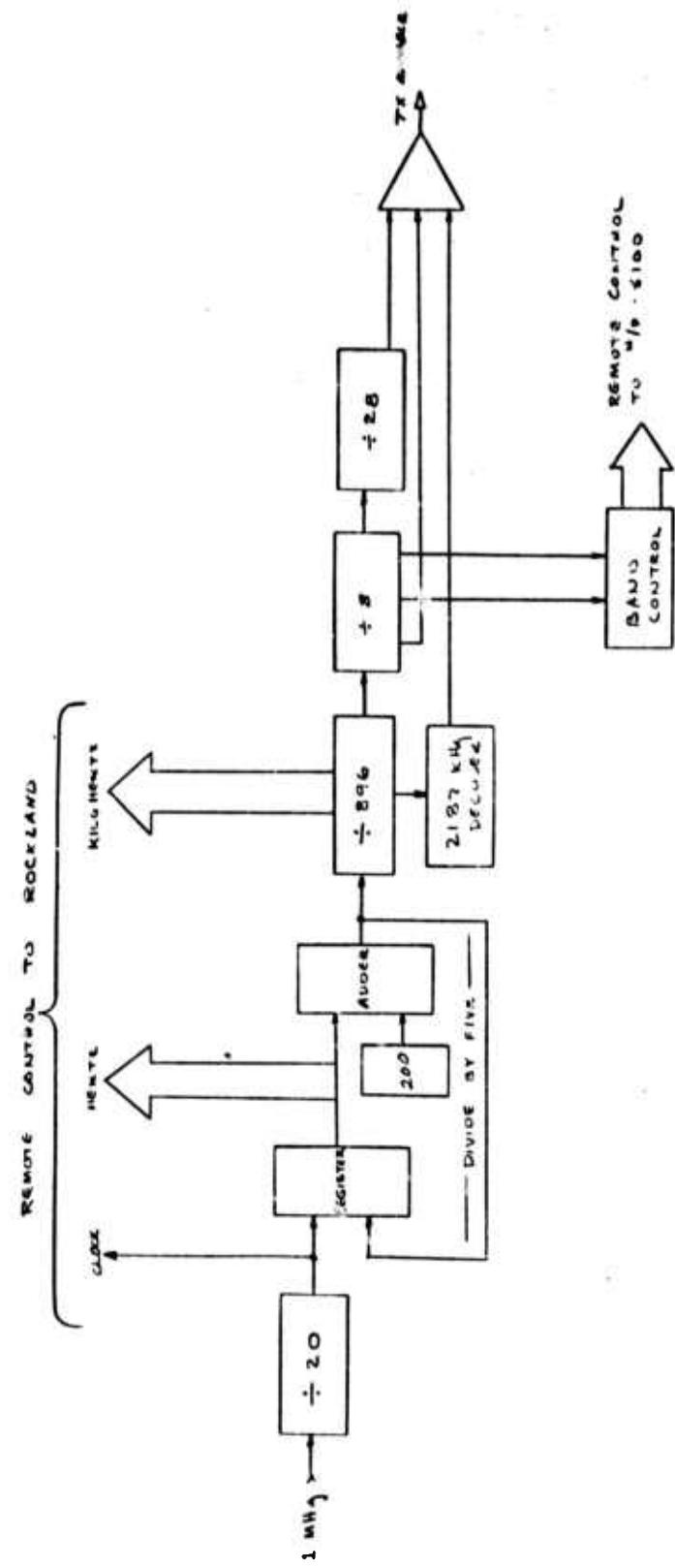


Figure 3-3. Transmitter Control

when the count exceeds 960 at the output of the adder, the register is reset to zero by the following clock pulse. At this time the divide-by-896 is incremented by one kHz. Both the Hz and kHz inputs are in pure binary code, but they must remain independent and not exceed an individual count of 1,000. Fixed frequency operation may be achieved by placing the Rockland synthesizer in Local control and manually selecting the operating frequency on the front panel controls. Figure 3-4 shows the control chassis front panel.

The Hz circuitry functions as a divide-by-5 and increments the kHz section every 100 microseconds. An entire band sweep requires 89.6 milliseconds. The first stage ($\div 2$) of the divide-by-8 following the divide-by-896 is utilized to "enable" the transmitter for alternate sweeps through the bands. This is possible because the divide-by-4 and 8 stages are used to control the band of operation. This provides two sweeps through each band before the band is incremented.

The band of operation may either be selected by the operator (fixed) or automatically sequenced in the AUTO mode. The band of R.F. operation is controlled by an injection from a Hewlett-Packard frequency synthesizer operated in the "remote" mode in a fashion similar to the Rockland synthesizer. The table below represents band and H-P synthesizer frequencies in MHz.

<u>Band</u>	<u>Frequency</u>	<u>Injection</u>
1	1.600 -- 2.496 MHz	37.4 MHz
2	2.700 -- 3.596	36.3
3	4.000 -- 4.896	35.0
4	5.100 -- 5.996	33.9

A 16 kHz gap around 2182 kHz (to protect a USCG distress channel) is vitiated by not "enabling" the transmitter. This produces a void in Band 1 but has no effect upon the timing and synchronization.

There are two fundamental timing sequences, AUTO and CONTINUOUS. In the CONTINUOUS mode, the transmitter sequences through the 4 bands every 716.8 milliseconds. This is the product of 4 bands times 2 sweeps per band (1 sweep without enable) times 89.6 milliseconds per band.

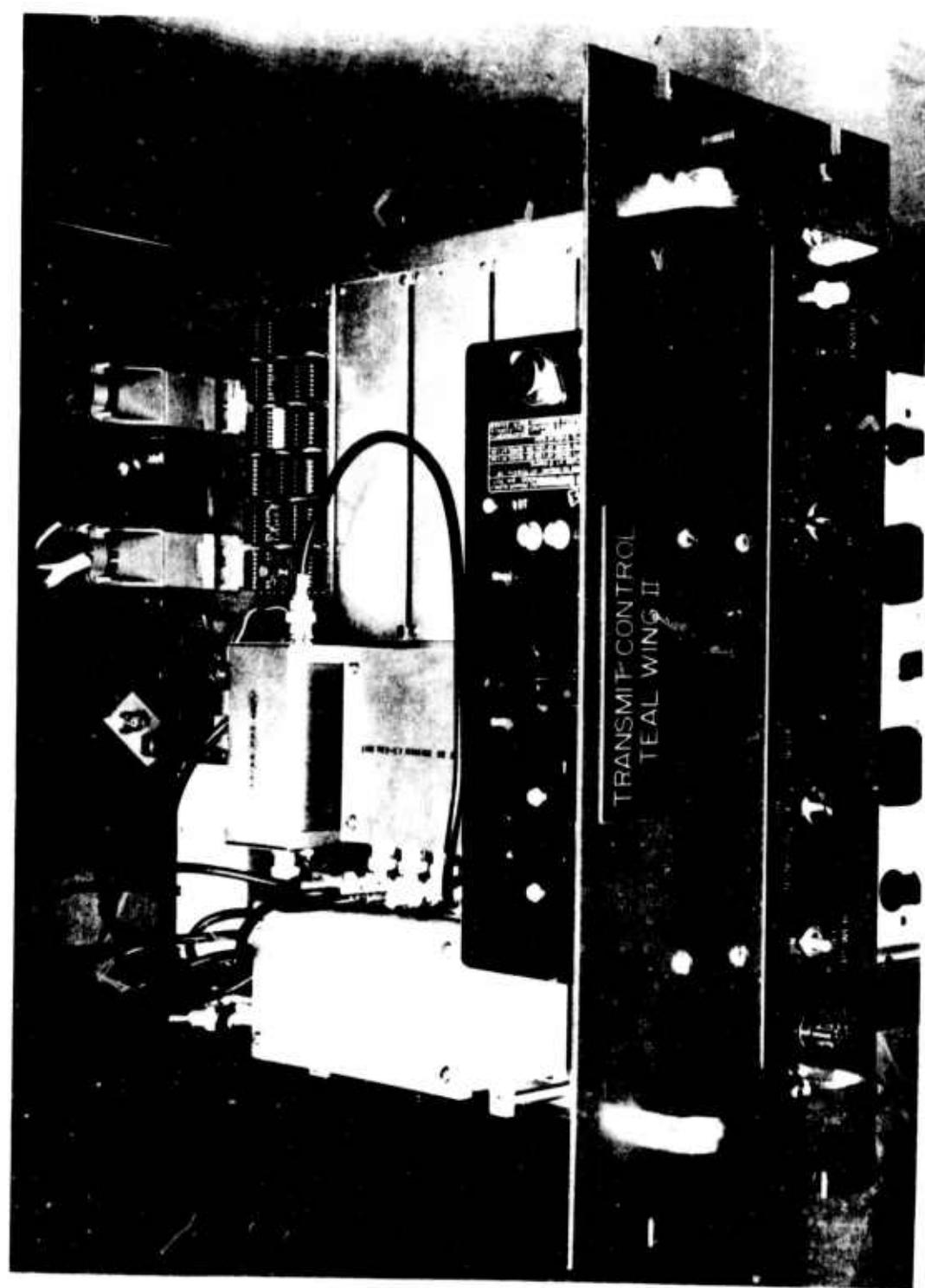


Figure 3-4. Transmit Control Chassis

The AUTOMATIC mode enables the transmitter to sequence through the four bands, or one band four times if manual band operation is selected by the operator, once every 20.0704 seconds. This is achieved by counting the band sequencing (716.8 msec) to select each 28th cycle.

A third mode, STAND-BY, is provided for synchronizing the counters to an external reference. This position of the mode switch disables the transmitter and forces the divide-by-8 and -28 to reset to their "enable" counts.

A front panel test point is provided for the operator's convenience. Additionally, an indicator on the front panel allows the operator to monitor the transmit-enable sequence.

The receiver control, Figure 3-5, retains much of the basic timing of the transmitter control. The difference is that the receiver timing may be advanced or retarded in increments of 10 usec, 1 msec, and 89.6 milliseconds to achieve synchronization (of the frequency scan, band, and 20.07-second intervals) between the transmitter and receiver. A second minor difference exists in the band increments generated by the H-P synthesizer output. These are offset from the transmitter injection by 667 Hz to provide an IF of 667 Hz in the receiver.

The injections required for the product detector are also generated by the receive control chassis. A 20-MHz output from the driver module of the H-P synthesizer is divided by 30,000 (7,500 x 4) to produce the 667 Hz injection. A Johnson counter is a divide-by-4 form provides two symmetrical outputs displaced 90 degrees in phase.

Data from the product detector module are input to a pair of sample-and-hold (S/H) amplifiers preceding their respective 12-bit analog-to-digital converters (ADCs). The clocking for both the S/H and ADCs is enabled during the "acquire" period at one-seventieth the rate at which the frequency is stepped. This relationship allows 64 samples per band. The output of the two ADCs is buffered and inputted as a single 24-bit word into memory. During a single sweep through the four bands, a total of eight sets of 64 samples each are inputted for a total of 512, twenty-four bit I and Q samples. This comprises a block of data in the computer and is identified by the "last word"

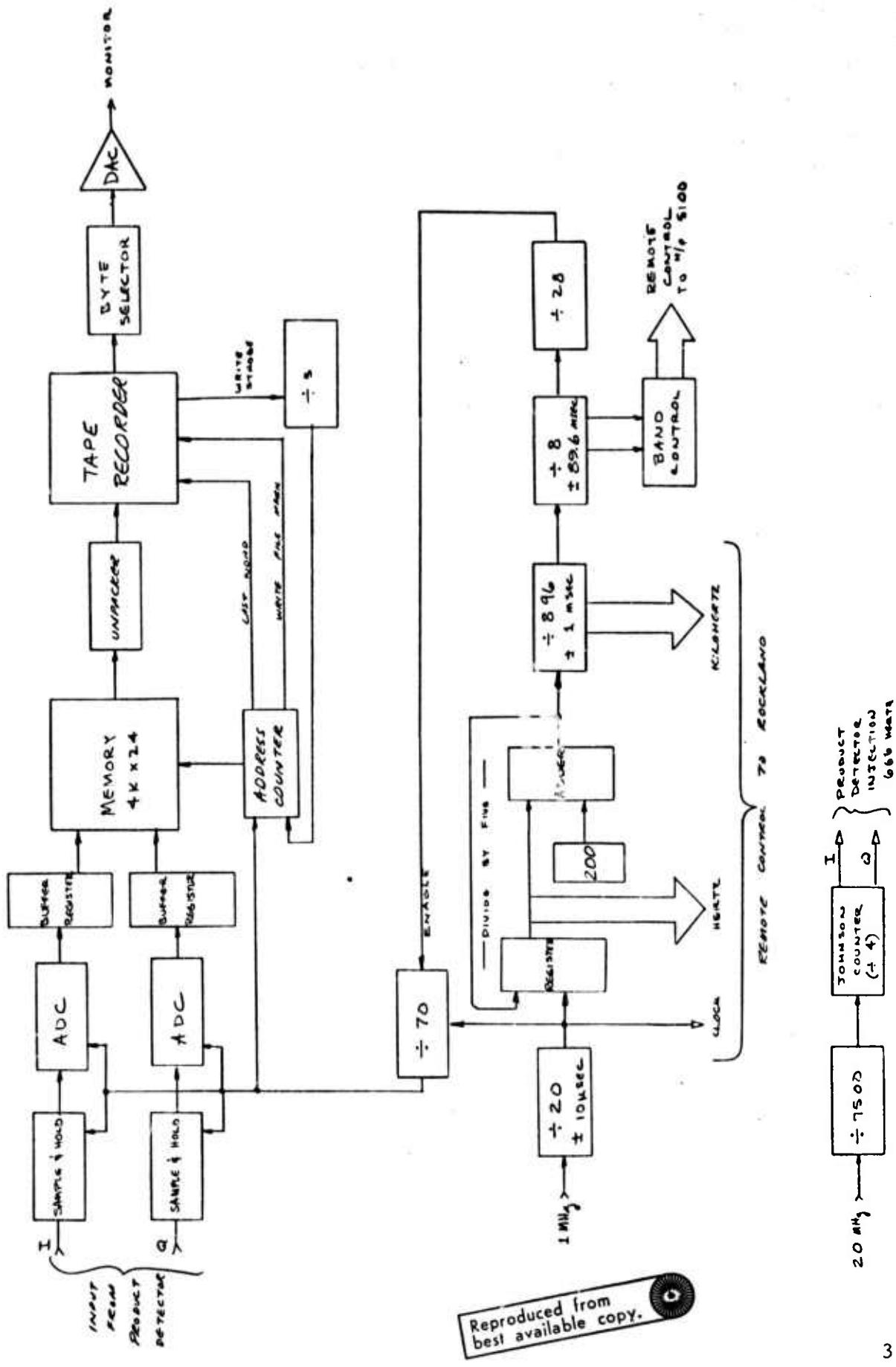


Figure 3-5. Receiver Control

command into the formatter of the tape transport. At the completion of eight such sets, a file mark is placed upon the tape and, regardless of the mode of operation of the Receive Control (i.e. AUTO, MANUAL, CONTINUOUS), the input sequence terminates and the transfer onto tape is initiated. A second file may be started by the operator by depressing the START SEQUENCE button. At this time, and until the file is complete, the front panel indicator will remain lit.

The tape recorder requires an 8-bit byte input, therefore the 24-bit data must be unpacked. Byte A contains the eight most-significant bits of the I channel. Byte C contains the eight most-significant bits of the Q channel. The remaining four bits of both I and Q data comprise the B Byte. (During off-line processing, the IBM 1130 computer program re-formats the data into 16-bit words to restore the I and Q integrity.)

The memory addressing is incremented by the Cycle-Complete outputs from the memory. Memory cycles are initiated in the Write cycle as the data is inputted. In the Read or Output cycle, Write Strobe output signals from the tape recorder initiate a memory cycle for every three bytes of input. This unit is shown in Figure 3-6.

The tape recorder provides a read-after-write output to allow monitoring of the recorded data. This output is loaded in a register which is connected to a digital-to-analog converter (DAC) to allow the operator to monitor the recording. Both a sync signal and a selector switch are provided to choose the particular byte displayed. The DAC is broken into two 4-bit halves to enable the B byte to be monitored.

3.4 MODES OF OPERATION

There are three basic modes of operation. The MANUAL mode inputs a block (512 samples comprising data from all four bands) each time the START SEQUENCE switch is depressed. Transfer onto the tape is automatic at the completion of each file. There are eight blocks per file. In CONTINUOUS, an entire 8-block file is inputted in response to depressing the START SEQUENCE button. The third mode, AUTO, inputs a block of data every 20.0704 seconds. As before, data is transferred onto tape automatically upon completion of the eighth block. The necessity of proper synchronization with the transmitter timing in this mode is apparent.

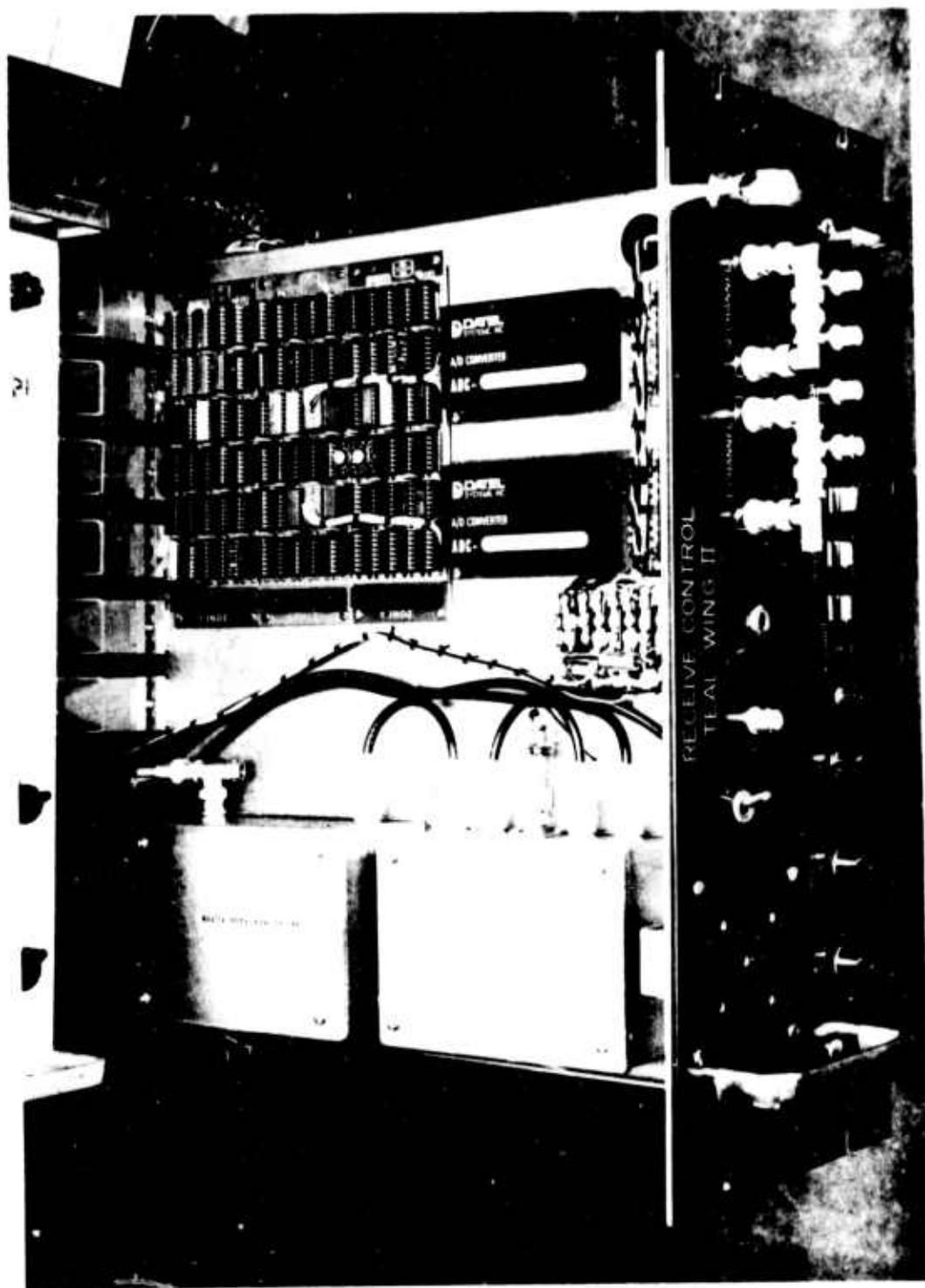


Figure 3-6. Receive Control Chassis

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Synchronism of the transmitter and receiver can be broken into three separate steps: the 20-second increment, synchronism within the wide band (10 kHz) output of the receiver, and optimizing the tracking while monitoring the product detector output (667 Hz bandwidth). Three operator controls are provided in steps of approximately 100 to 1. While any of these three switches is actuated for either Advance or Retard, the relative timing of the receiver with respect to the transmitter will change once every 716.8 msec. Either 10 μ sec, 1 msec, or 89.6 msec increments may be chosen, depending upon which of the three switches is used.

Band selection must be made by the operator unless the AUTO mode is selected, in which case the equipment will automatically sequence through the four bands.

Coarse synchronization should be accomplished with both the transmitter and receiver in the AUTO mode. If the band switches are not in the AUTO position, it is possible to lock-up on the wrong phase of the band sequence when returning to AUTO. This may be easily corrected later by carefully stepping the COARSE timing in either direction while in AUTO mode since the 89.6 msec increment is one-band duration. After satisfactory individual synchronization to a common 20-second reference, the CONTINUOUS mode should be used to attain a receiver output by means of the MEDIUM timing control. It is important at this point to know whether RETARD or ADVANCE should be selected. As soon as an output from the receiver 10 kHz wideband port is obtained, the operator should utilize the audio output of the receiver in conjunction with both the MEDIUM and FINE timing control to optimize the zero I.F. output of the product detector.

Precise operator instructions were given in the Experiment Plan, an appendix to the end-of-June technical progress report.

4. PRELIMINARY CHANNEL MEASUREMENT RESULTS

This section describes the initial results obtained from a continuing analysis of the channel measurement data. The data collected at Portland, Me., has not been processed, and only a small fraction of the West Quoddy, Me., measurements have been analyzed at this time. Specifically, only representative samples of data collected over the 220 nm path during the daylight hours on the 29th, 30th, and 31st of August have been analyzed. (Nighttime data are not available for this path as the high nighttime interference level made it impossible to collect useful data.) The analysis of these data has produced a consistent result, however, being that, at the frequencies and bandwidths of interest, surface-wave-propagated signals experience no significant phase distortion.

Four basic types of data presentation are used to display the results of the analysis. Spectrograms which are the equivalent of a compressed pulse waveform are presented for three different cases: (a) the exciter output signal when directly coupled into the receiver; (b) the surface-wave-propagated signals; and (c) the skywave-propagated signals. In these plots, nonlinear changes in signal phase, resulting from signals of different frequencies either traveling over slightly different paths, or taking different amounts of time to travel over the same path, produce a distortion of the signal in the form of a smearing in time. These spectrograms permit the presence or absence of frequency dispersion to be determined in qualitative terms.

A second type of presentation, where measured values of phase angle are plotted as a function of frequency, is used to explain how dispersion was characterized quantitatively in terms of "distortion factors." Two such plots are presented. One is for surface-wave-propagated signal and one is for a signal which reached the receiving antenna via the F-region of the ionosphere. In each case, a constant and linear variation of phase with frequency was removed before the data were plotted, as a means of normalizing.

All of the distortion factors currently evaluated are plotted as a function of frequency band in the third type of display presented. As indicated in the end-of-June progress report, the channel measurements were made with an FM sounding system having an instantaneous frequency which varied approximately linearly over one of four possible 897 kHz bands of frequencies at the rate of 10 MHz per second. The band limits were 1.600-2.496, 2.700-3.596, 4.000-4.896, and 5.100-5.996 MHz, respectively. The amplitude and phase of the deramped signal appearing at the output of the receiver was sampled at 1.4 ms intervals, corresponding to a 14 kHz change in the test frequency between measurements. Distortion factors were computed only for those sweeps where a significant majority of the frequencies sampled had a signal-to-noise ratio (SNR) exceeding 15 db on the average.

Over half of the sweeps examined thus far have failed to meet this SNR criterion. Indeed all data collected in the 5.100-5.996 MHz band have failed to meet this criterion, which, of course, was imposed for the obvious purpose of restricting attention to only the most accurate measurements.

In the fourth type of diagram, distortion factors are presented in terms of the loss in processing gain which would be experienced by correlators designed to process signals with bandwidths ranging between 70 and 742 kHz, if the signal being received was distorted by an amount corresponding to one of the distortion factors.

The normal response of the channel measurement receiver to the transmitted signal is illustrated in Figure 4-1. In this case, the receiver was directly connected to the output amplifier of the transmitter via a short length of coaxial cable. An RF attenuator was used to reduce the signal power to an acceptable level which, as indicated in Figure 4-1, resulted in an average SNR of 36 db. This plot of the undispersed signal can be used as a reference against which those representing surface wave and skywave propagated signals can be judged.

In this and all subsequent cases, the quoted value of SNR was obtained by averaging over both time and frequency. As previously stated, the transmitter was turned off on alternate sweeps allowing the noise environment to be sampled at the receiving site on exactly the same frequencies to be

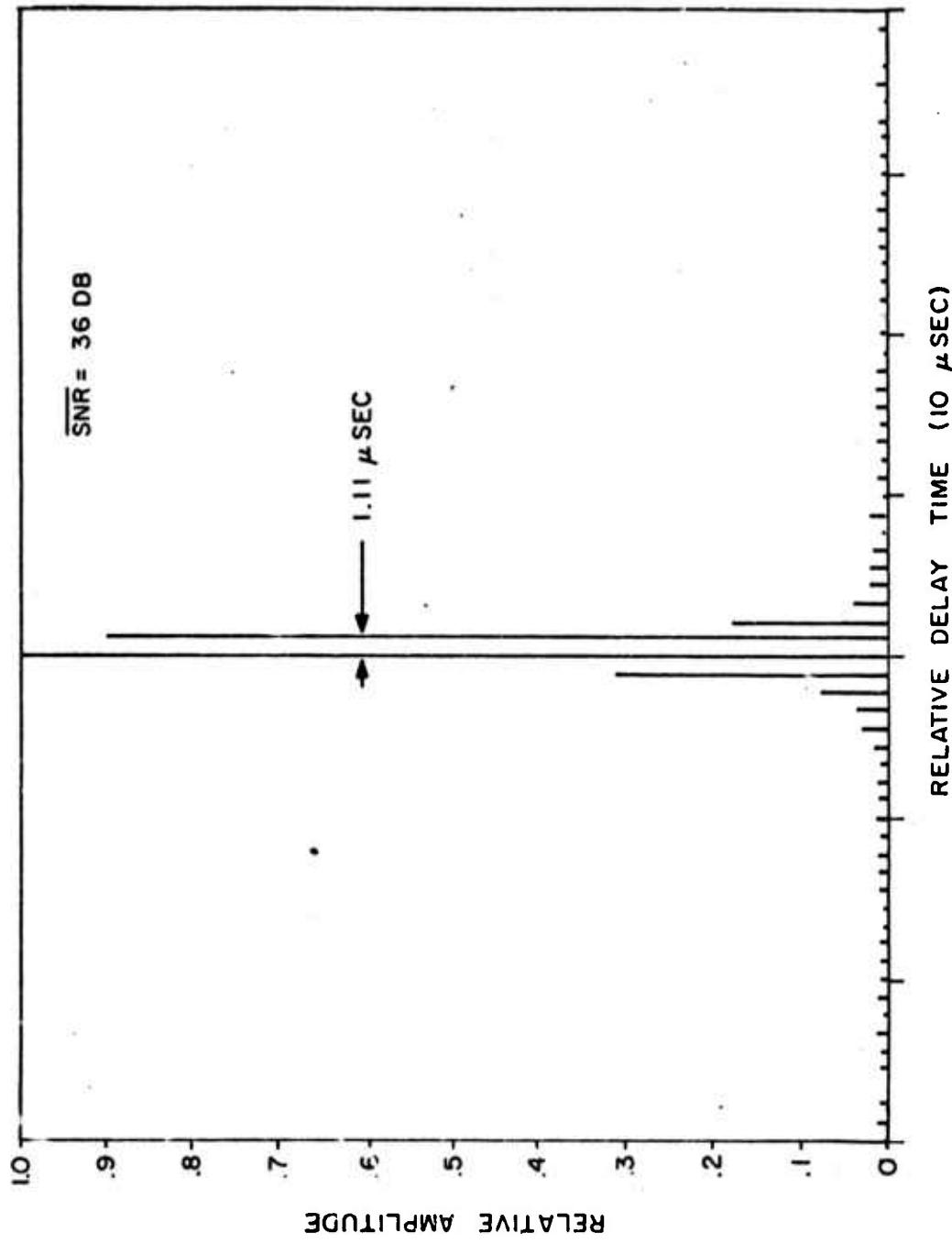


Figure 4-1. Spectrogram of the Received Signal When the Receiver was Directly Coupled to the Exciter Output via Coaxial Cable

sampled with the transmitter turned on. These separate measurements of signal-plus-noise and of noise-alone were used to form the SNR values which were averaged together. All sample points from seven pairs of sweeps were included in the average.

4.1 SPECTRAL ANALYSIS

A spectrogram of the surface-wave-propagated signal is presented in Figure 4-2. This particular spectrogram is for a single sweep over the frequencies of Band-2, but it is representative of all of the data examined thus far in the analysis. Except for differences in SNR, the spectrograms obtained for the surface-wave-propagated signals do not differ in any perceptible way from that obtained when the receiver and transmitter were connected via coaxial cable, indicating that the surface wave channel did not distort the signal to any sensible degree.

4.2 COMPARISON WITH SKYWAVE DISPERSION

Since the surface wave signals were so obviously free of dispersion, it was deemed appropriate to examine a few skywave signals for the specific purpose of demonstrating that the channel measurement apparatus was capable of measuring such distortion when it was present. Signals reflected from both the E- and F-regions of the ionosphere were examined. Differences in arrival time were used to separate these signals from the first-arriving surface wave signals.

As expected, the E-region signals were only slightly more dispersed than the surface wave signals, whereas the F-region signals showed much more dispersion. The spectrogram of one of the few cases examined, where the signals reached the receiving antenna via the F-region, is shown in Figure 4-3. The average SNR for this case is not much different from that for the surface wave case considered previously, being 23 db as compared to 26 db for the surface wave case. Yet the "apparent" noise level is much greater than this SNR would indicate, and the "noise" has characteristics similar to those of the signal. The obvious conclusion is that the signal

*When the system's processing gain is taken into account, the noise level should be in excess of 40 db below the peak shown in Figure 4-3 and would barely be indicated.

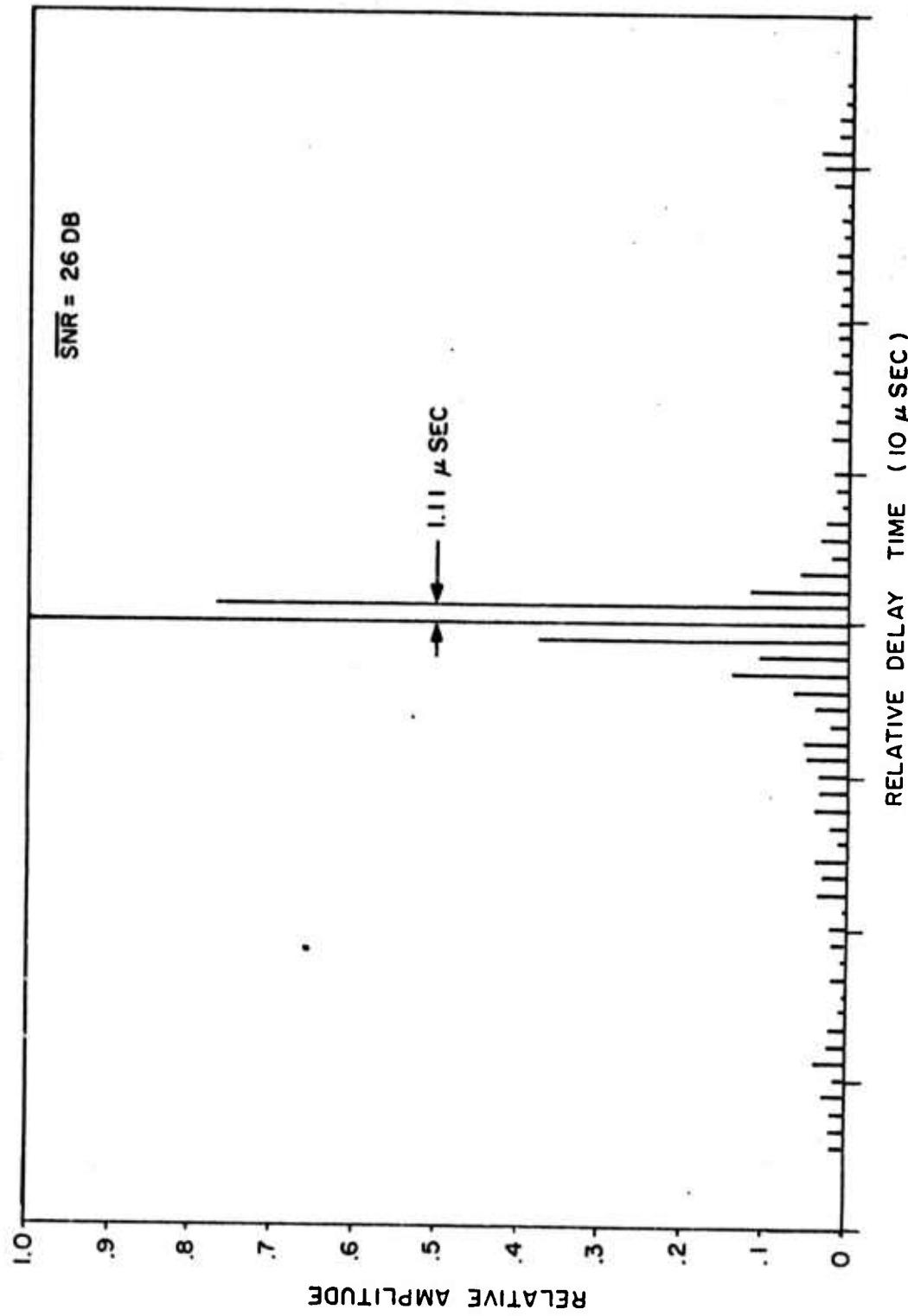


Figure 4-2. Representative Spectrogram of Surface-Wave-Propagated Signals

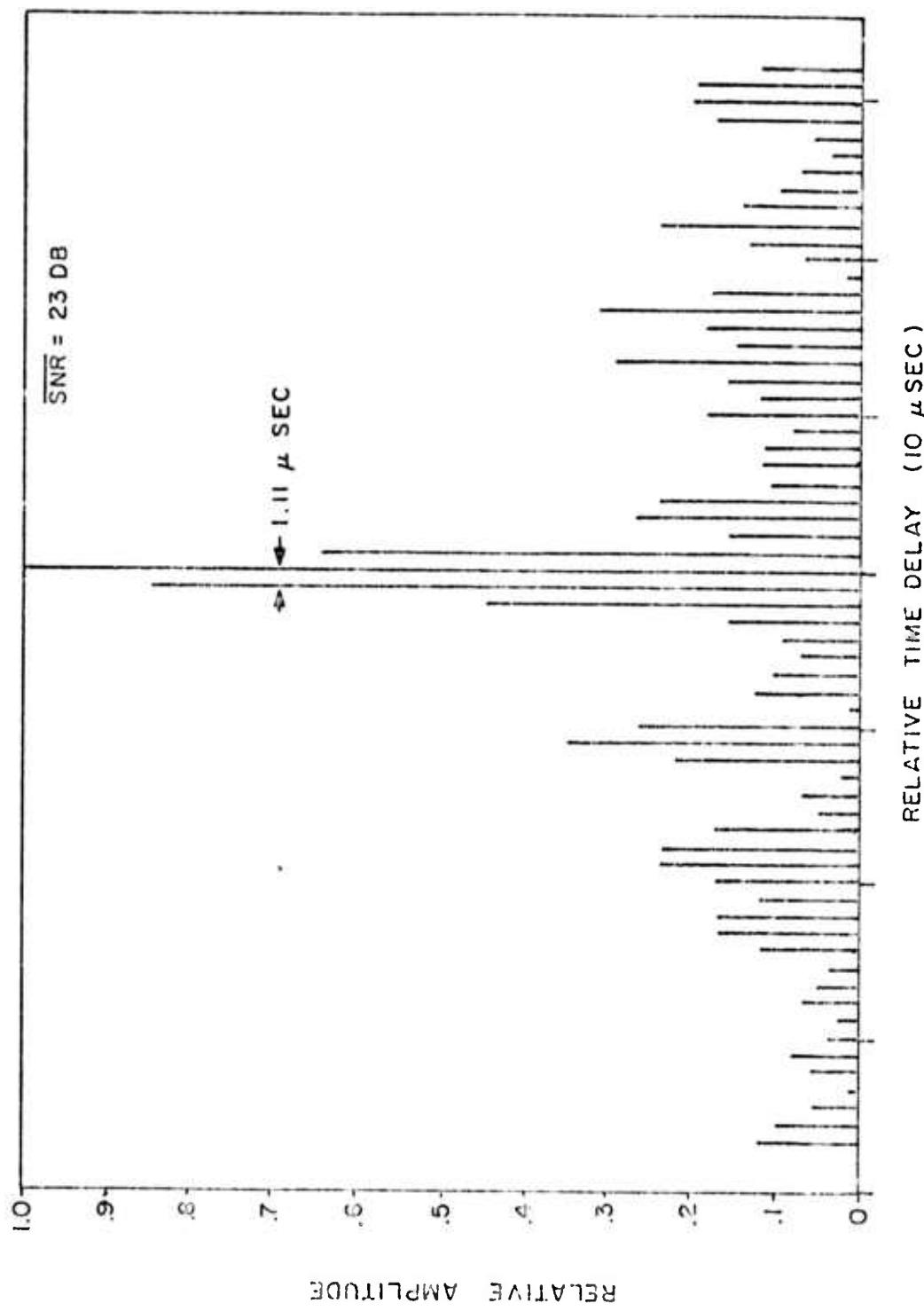


Figure 4-3. Spectrogram of Signals Propagated via the F-Region of the Ionosphere

energy had been dispersed by the ionosphere and thus reached the receiver throughout the entire observation period of about 67 μ s.**

The phase angles measured for the skywave signal displayed in Figure 4-3 are plotted as a function of frequency in Figure 4-4. If there were no phase distortion introduced by the channel, a linear relationship would exist between phase angle and frequency. But, as can be seen from Figure 4-4, the relationship between phase angle and frequency is not linear in this case, indicating that the phase of the signal had been modified by the medium through which it propagated.

4.3 CHARACTERIZATION OF DISPERSION

One obvious way of characterizing the amount of dispersion introduced by the medium is to fit a polynomial to the data and to use the coefficients of the second and higher order terms as "distortion factors" to indicate the magnitude of the distortion. A quadratic function was found to provide a reasonable fit to the data of Figure 4-4. Thus, only one distortion factor (with units of deg μ sec²) is required in this case, namely, the coefficient of the second order term, or 4018 deg μ sec².

As indicated in Figures 4-5 and 4-6, a second order distortion factor of 4018 for signals reflected from the ionosphere is large compared to those obtained for the surface wave channel. Figure 4-5 is the phase angle vs. frequency plot for the surface wave data previously shown in Figure 4-2. For all practical purposes, a straight-line relationship exists between phase angle and frequency--meaning that the signals were not phase distorted by the channel. Nevertheless, a quadratic function with a second order coefficient of -29.7 was found to fit the data slightly better than a linear function. This small factor is not considered to be significant in terms of the unrealized processing gain which would be experienced by a communications system receiving signals distorted by this amount.

**The length of the observation period was set by the sweep rate of 10 MHz/sec and the data bandwidth, which was about 667 Hz at its half-power points.

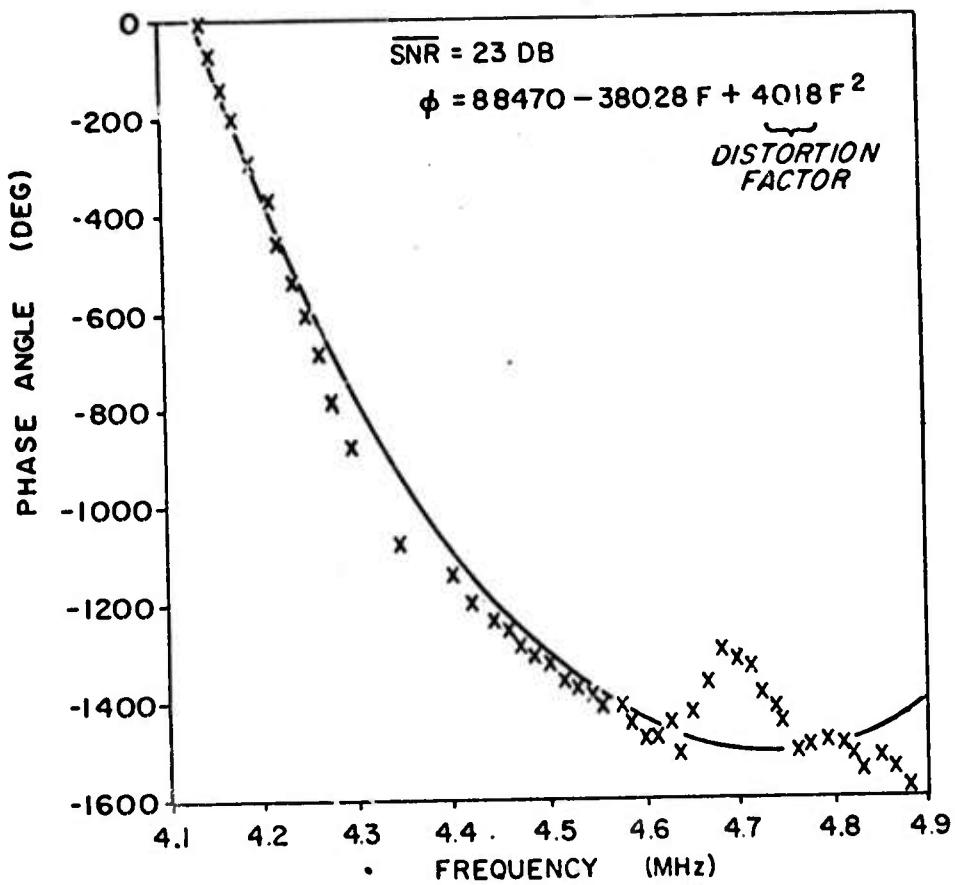


Figure 4-4. Phase Angle vs. Frequency Plot of F-Mode Data of Figure 4-3

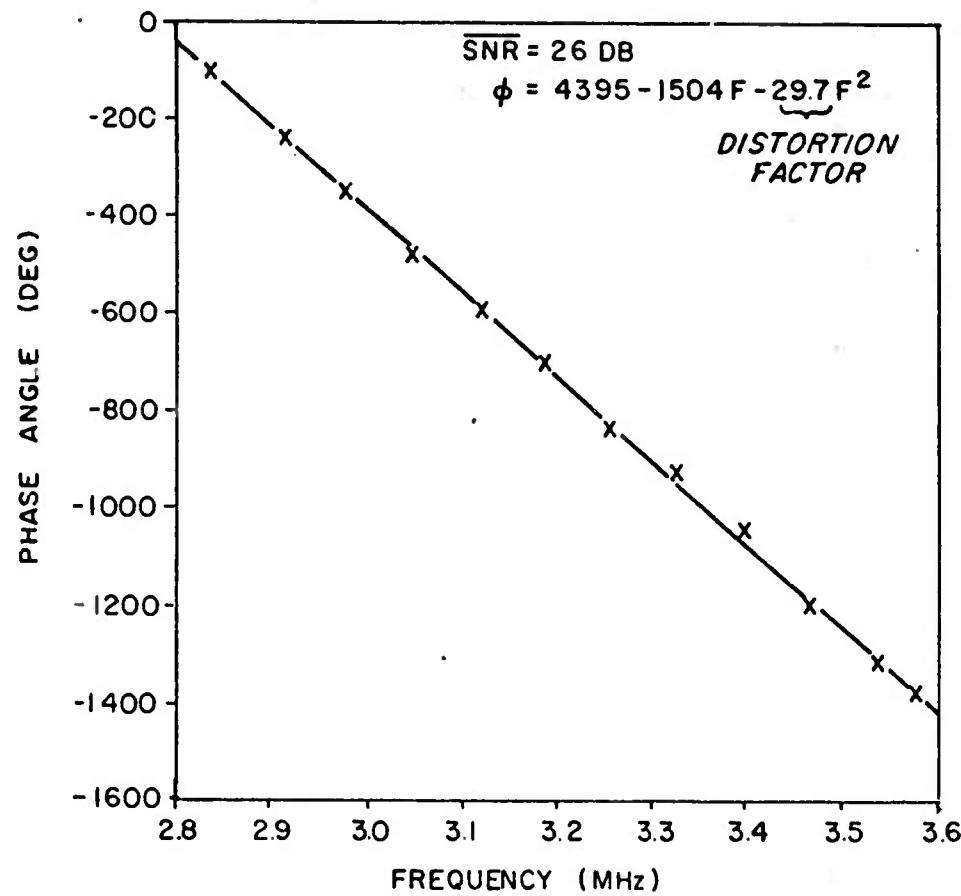


Figure 4-5. Phase Angle vs. Frequency for the Surface Wave Data of Figure 4-2

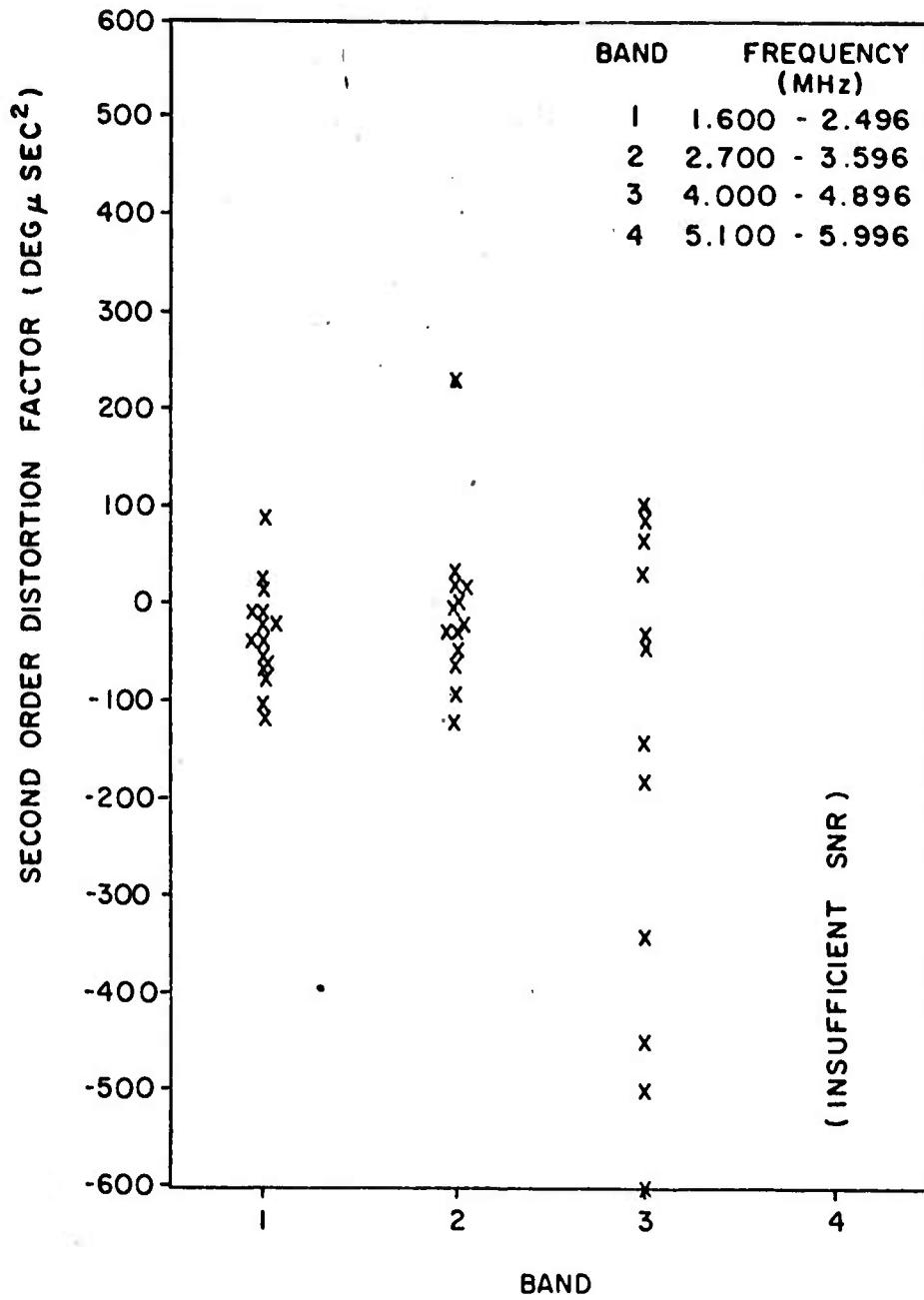


Figure 4-6. Surface Wave Distortion Factors as a Function of Frequency Band

As will be shown later the distortion factor must be at least one or two orders of magnitude larger than ± 29.7 to be significant, with the exact point of significance depending upon the bandwidth of the communications system.

Figure 4-6 is a plot of distortion factors obtained for surface wave propagated signals. They are presented as a function of frequency band, with each point on the plot representing one sweep of the stepped sounder over the indicated band of frequencies. Two general time periods are represented by the data of Figure 4-6, early morning and mid-afternoon. Exact times and dates are given in Table 4-1.

Sea state hindcasts are also given in Table 4-1 for the data presented in Figure 4-6. These hindcasts are a combination of data provided by both the U.S. Naval Oceanographic Office in Washington, D.C. and the Master of the M/S BOLERO. They are appropriate for the great circle path between the transmitting site at the Race Point Coast Guard Station on Cape Cod, Mass. and the receiving site near West Quoddy Head, Me. According to these hindcasts, a smooth sea prevailed throughout the period represented by the results of Figure 4-6. There were no swells in evidence and the wind waves were never more than 2 feet high.

Three features of Figure 4-6 should be noted. Note, first of all, that there are no points plotted for Band-4 (5.100-5.996 MHz). Two factors combined to produce values of SNR at Band-4 frequencies which were much lower than that needed for accurate measurements of phase angle. They are: (1) relatively high attenuation of the desired surface-wave-propagated frequency; and (2) relatively low attenuation of sky-wave-propagated noise and interference. Usually only one or two specific frequencies within the 5.1-6.0 MHz band had an average SNR greater than 15 db.

The same combination of factors was still making itself felt at the Band-3 frequencies (4.00-4.896 MHz) and is thought to be the main cause of the relatively large spread in the distortion factors obtained for this band. Distortion factors ranging from +100 to -600 were obtained on the Band-3 frequencies. Should it turn out that this spread of values is not entirely due to having fewer points over which to fit the quadratic function, as a result of

Table 4-1
Sea State Hindcasts for the Data Presented in Figure 4-6

Date	Time (EST)	Wind (All Beauforts-2)		Waves	Swell
		Direction	Height (Feet)		
8/29/73	0709	N	1	2	None
8/29/73	1512	N	1	2	None
8/29/73	1555	WNW	1	2	None
8/29/73	1605	WNW	1	2	None
8/30/73	1639	SW	2	2	None
8/30/73	1710	SW	2	2	None
8/31/73	0710	N	1	2	None
8/31/73	0725	N	1	2	None
8/31/73	0731	N	1	2	None
8/31/73	0734	N	1	2	None
8/31/73	0735	N	1	2	None
8/31/73	1330	None			None
8/31/73	1415	None			None

generally lower values of SNR, then a small amount of dispersion must be attributed to the channel. Additional analysis is required to resolve this point.

Signal-to-noise ratios were generally larger at frequencies below about 4 MHz. Skywave interference was lower because of greater attenuation of signals passing through the D-region of the ionosphere and signal strengths higher because of lower surface wave attenuation losses.

The third and last feature of interest in Figure 4-6 is that the distortion factors obtained for Bands-1 and 2 are tightly clustered near zero, indicating only insignificant phase distortion, if any.

The amount of unrealized processing gain (distortion loss) expected to be associated with distortion factors of different magnitude is given as a function of bandwidth in Figure 4-7. Values of distortion loss were derived in accordance with the algorithm of Table 4-2 for just enough different values of distortion factor to indicate the trend. It will be noted that in some cases the derived values of loss for a given bandwidth do not fall exactly on the smooth curve eye-fitted to the data. This was unexpected and, as-yet, unexplained. The reason for this small discrepancy is being investigated and should be determined in the near future.

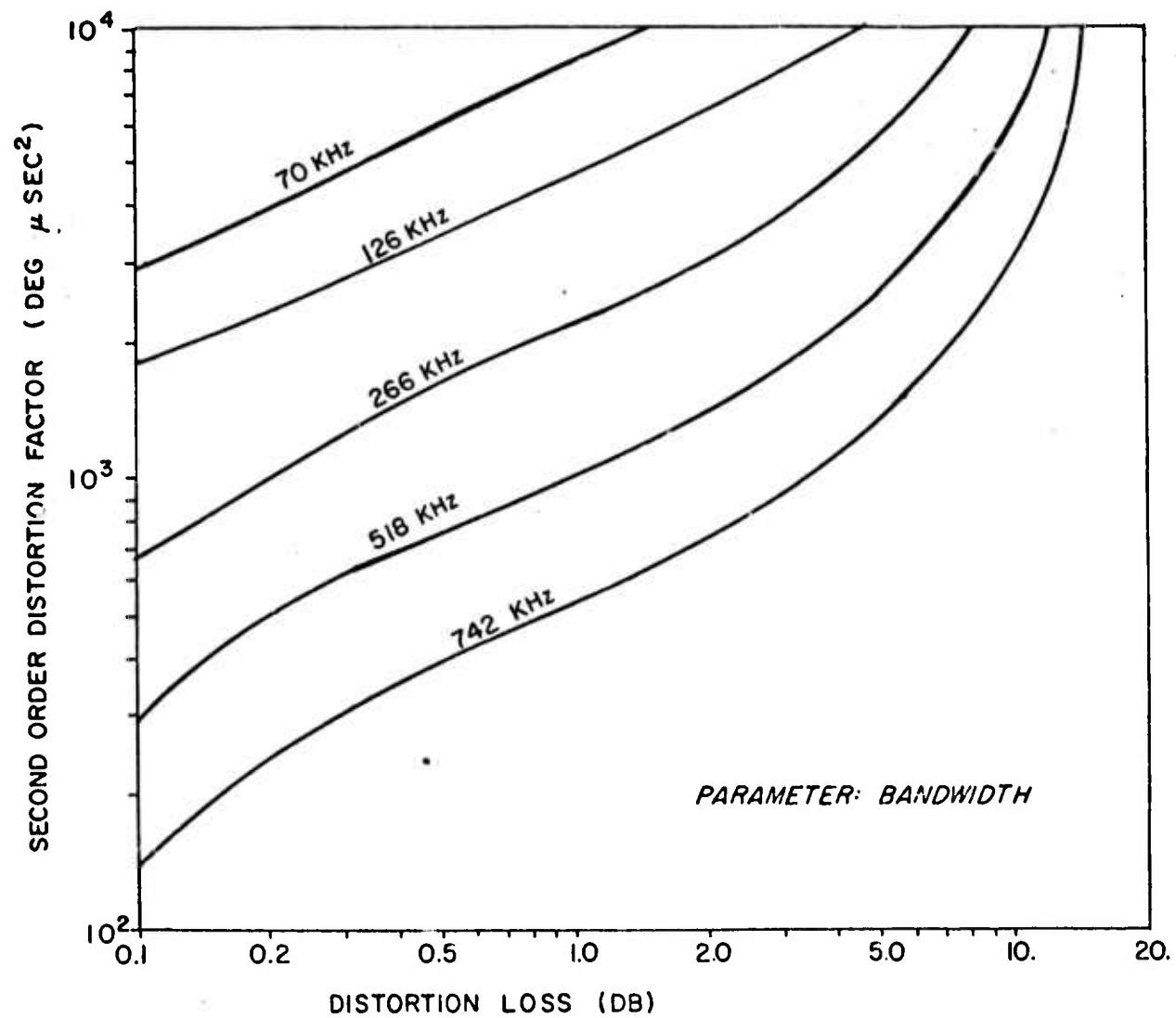


Figure 4-7. Derived Relationship between Distortion Factor, Distortion Loss, and Signal Bandwidth

Table 4-2
Algorithm Used to Derive the Distortion Loss Values of Figure 4-7

1. Compute 64 values of phase angle (ϕ) spaced at 14 kHz intervals for 9 different values of distortion factor, using the expression

$$\phi = C_0 + C_1 f + C_2 f^2$$

where $C_0 = C_1 = 0$

C_2 = distortion factor = 300, 500, 1,000, 1,800, 2,500, 4,000, 5,000, 7,500, and 10,000 respectively

and f is expressed in MHz

2. Compute the phase deviation from linearity ($\Delta \phi$) on a point-by-point basis for each set of data. (This was accomplished by comparing the computed values from step 1 with those corresponding to a straight line curve fitted through each set of data by the method of least squares.)
3. Assuming unit amplitude for each sample value, compute the scalar sum of all sample points falling within a bandwidth of given dimensions, centered on the 37th and 38th sample points. (The sum of all amplitudes falling within a bandwidth of 70 kHz, for example, would be 6 units. For a bandwidth of 742 kHz, it would be 54 units.)
4. Compute the magnitude of the vector representing the sum of all sample values falling within the specified bandwidths ($|V|$), taking into account the phase deviations from linearity derived in step 2, i.e., compute

$$|V| = \left[\left(\sum_{i=1}^n \cos(\Delta \phi)_i \right)^2 + \left(\sum_{i=1}^n \sin(\Delta \phi)_i \right)^2 \right]^{1/2}$$

for each combination of bandwidth and distortion factor, where n = number of sample values included by the bandwidth.

5. Compute distortion loss in decibels, where

$$\text{distortion loss} = 20 \log_{10} \frac{\text{Scalar Sum}}{|V|}$$

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4-14